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SOME AREAS OF LANDSLIDE ACTIVITY IN VICTORIA, AUSTRALIA

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ABSTRACT: Four areas of landslide activity have been studied in Victoria, and these demonstrate the types of landslide which occur on two susceptible local rock types, Early Cretaceous arkose and mudstone, and Tertiary clay-rich sediments.

A detailed study of the geomorphological processes, rock structure and mechanisms of weathering and alteration operating in the *Windy Point area* along the Great Ocean Road, south of Lorne, has lead to an understanding of the causes of the landslide activity. The noted instability of the Early Cretaceous sediments in the Windy Point area is due to the strong jointing, the steep slopes with active undercutting by ocean and rivers, and most significantly weathering along the planar discontinuities of beds and joints. The presence of relatively fresh feldspar in the weathered arkose leads to crumbling, toppling and rock sliding rather than flow. A slope stability map of the Windy Point area has been prepared to show the most unstable areas.

At *Eastern View*, shallow compound rotational slides and flows on steep, cleared slopes occur in weathered Early Cretaceous arkose and mudstone, above the regolith-rock boundary.

Shallow earth and mud flows and deeper rotational slides occurring in the *Parwan Valley* and *Werribee Vale area* are due primarily to the high clay content of the poorly-cemented Tertiary sediments.

Flow failures and shallow slides within the soil developed on Tertiary sediments at *Lake Bullenmerri* appear to be due in part to the presence of montmorillonite from the decomposition of adjacent basaltic lava, together with a high degree of water saturation.

INTRODUCTION

The study of the stability of slopes, both natural and excavated, encompasses a broad range of scientific disciplines. A geomorphological approach has been used in this study of several areas of landslide activity in Victoria.

The *Windy Point area*, along the Great Ocean Road, south of Lorne, has been dealt with in detail as both natural slope failures and failures related to road construction are well known. The Early Cretaceous arkoses and mudstones such as occur at Windy Point appear to show a greater degree of instability than any other rock type in Victoria. Slides and flows on weathered Early Cretaceous sediments have been studied at *Eastern View*, north-east of Lorne.

The largely unconsolidated Tertiary sediments of Victoria are also noted for their instability, and two areas of landslide activity have been studied. The *Parwan Vallely* and *Werribee Vale area* shows numerous slide and flow failures in Tertiary sediments, and flow failures are also found on the north-west slope of *Lake Bullenmerri.*

The four areas studied are shown in Fig. 1. A general review of landslides in Victoria showing all known areas has been published elsewhere (Evans & Joyce 1974).

The classification of slope movements used in this study is that outlined by Nemčok et al. (1972). From a kinetic viewpoint the four broad groups of creep, sliding, flow and fall can be distinguished. Each group has been further subdivided according to the type of failure and the material involved, using criteria proposed by Coates (1970) and Hutchinson (1968). Where no genetic connotation is intended, the term 'landslip' has been used. The term 'landslide' covers those relatively rapid down-slope movements of soil and rock masses which occur primarily as a result of shear failure at the boundaries of the moving mass.

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FIG. 1—Location of areas studied.

In slope stability studies there are two distinct types of failure. The material is regarded as a 'soil' where failure is governed by a surface passing through initially continuous material, but if the failure is governed by a surface developed along weak planes such as bedding or jointing, the material is considered to be 'rock'. Slope failures in the Windy Point area are essentially in rock masses, but the landslips in the three other areas studied are in 'soil'.

This article is based on a B.Sc. (Hons) Report prepared in 1973 by R. S. Evans under the supervision of E. B. Joyce in the School of Geology, University of Melbourne. R. S. Evans was responsible for the field and laboratory data.

THE WINDY POINT AREA

Landslipping throughout the Otway Ranges is well known and has long been a problem in road construction. The Windy Point area is south of Lorne, 118 km south-west of Melbourne, and is bounded by the St. George River on the north and the Cumberland River on the south, and extends an average 1·75 km inland from the coast (see Fig. 2). The study of the geology and geomorphology of this area, with both ancient and active landslips present, has given a better understanding of the processes and mechanisms involved.

The geology of the Lorne district has been described by Edwards (1962). This article looks more closely at factors such as weathering, and jointing. These influence the slope stability of the area, and this study leads to some conclusions on the stability of slopes on the Early Cretaceous rocks of Victoria.

GEOLOGY

The Early Cretaceous rocks of this part of the Otway Ranges consist primarily of freshwater interbedded arkose and mudstone, which have been broadly folded into a large plunging anticline during the Pliocene elevation of the Otways (Edwards 1962). The massive arkoses are strongly jointed and tend to show a regular pattern in the orientation of joints in relation to the fold axis. Several of the hills are capped with a thin veneer of Tertiary sands.

The petrology of the Early Cretaceous rocks of the Otway Ranges has been described by Edwards and Baker (1943); a brief description is included here. The main rock type is an arkose with the interbedded mudstone being far subordinate in volume.

The arkose when fresh is dark greenish-grey in colour and has a somewhat speckled appearance. Grain size analysis shows that the texture of the arkose is mainly fine sand size. Quartz

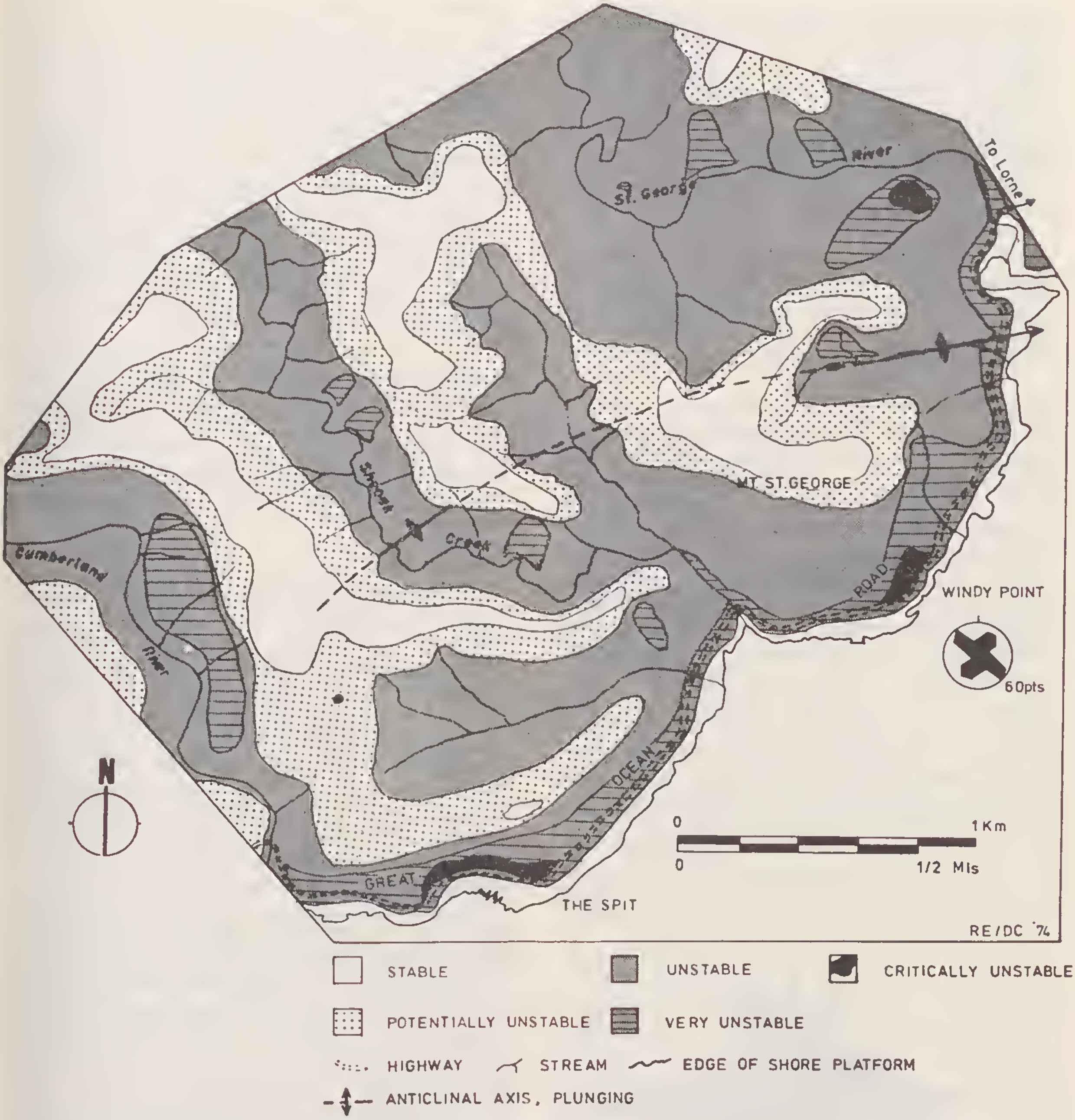

FIG. 2—Slope stability map of the Windy Point area, near Lorne, also showing the George Anticline, and a joint rosette for Windy Point area. Base Map Beech Forest B. Department of Lands, Victoria (1957).

and feldspar make up the bulk of the rock with the feldspar being a mixture of oligoclase, and some orthoclase. The feldspars are clouded and speckled, even in the freshest samples. The cement consists of a complex assemblage of chlorite, biotite, carbonate, sericite, clay minerals and a little epidote. The greenish colour of the arkose is due to the chlorite cement. Edwards and Baker (1943) reported that kaolinite was the chief clay mineral, but x-ray diffraction analysis indicates that illite is the most abundant clay mineral in the study area, although kaolinite is present in some samples analysed.

The interbedded mudstones and shales are blue or grey-green in colour and are well-bedded, tending always to break along the bedding. These very fine-grained rocks commonly contain a mixture of sericite and clay minerals, mostly illite and kaolinite, with a little fine angular feldspar and quartz. Edwards and Baker (1943) state that the mudstone consists of clays which are liable to base exchange and contain iron-rich clay minerals, in which the bulk of the iron is in the ferrous state. Grim (1939) points out that the common clay mineral of this type is illite.

Thin black coal seams are common both within the arkose and the mudstones, but tend to be more numerous in the arkose. Edwards (1962) believed that the burial depth was between 700 m and 760 m which would imply that the associated clays are strongly overconsolidated.

WEATHERING AND ALTERATION

The mechanism of breakdown of the Early Cretaceous arkose and mudstones and the products formed are very important in this study. Even in the freshest arkose, the feldspars are a little cloudy due to some decomposition; however, as weathering progresses, even to advanced stages, the feldspars remain relatively unchanged. Thin sections of very weathered samples show that breakdown occurs within the matrix, while the framework remains fresh. Grain size analysis of a weathered arkose shows that only a small proportion of the rock, that is the matrix, actually changes in grain size. Fresh arkose breaks across the grains, indicating the strength of the cement, but a weathered arkose is friable and crumbles easily, the relatively coarse feldspar grains producing a distinctly non-cohesive mass.

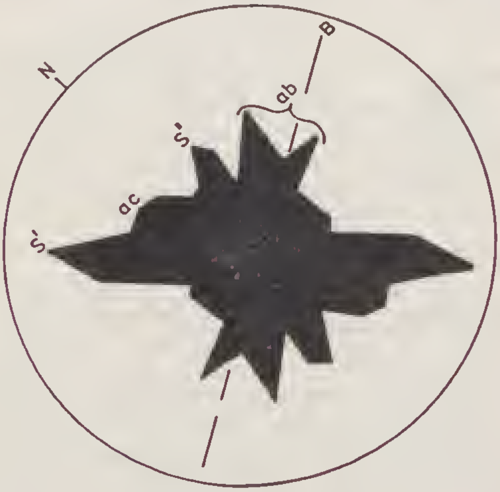

Fig. 3—Joint rosette for the George Anticline. Rosette Interval: 10°, 324 points. B is the statistical average of the strike of the fold axis.

Both the porosity and permeability should be changed by this alteration. Edwards and Baker (1943) stated that the increase in porosity with weathering arose from a volume shrinkage of the cement as the chlorite changed to limonite. The permeability should also increase as the fresh feldspar grains will tend to keep the weathered particles apart. The soil produced on the arkose tends to be immature, being little more than crumbled rock formed by the alteration of the matrix. Ferrous carbonate that may be present in some rocks is altered to limonite. Similarly, chlorite alters to limonite, producing a colour change from greenish-grey to brown.

The mudstones and shales tend to weather faster than the arkose. They produce a very cohesive brown to pale orange clay, composed largely of illite and kaolinite. The presence of thin coal seams could have a significant effect on weathering by producing organic acids which may accelerate the breakdown of cementing minerals.

STRUCTURE

A broad anticline dominates the structure of this section of the Otway Ranges. It is known as the George Anticline, as the fold axis outcrops in the exposed shore platform 200 m south of the mouth of the St. George River (Fig. 2). At this location the fold axis trends at 77° and plunges 15° east-north-east. This approximately symmetrical fold has dips on each limb of 25° to 37° and tends to show a curvature along its axis, with the south-western end of the fold axis curving to the south. This distinct warping to a trend of 36° can be seen clearly in aerial photographs of the shore platforms.

Near the Cumberland River the beds dip at low angles of approximately 5° east and the strike is approximately north, but varying greatly. Edwards (1962) and Medwell (1971) proposed a fault in this locality and the abrupt change of dip and strike suggests a fault striking at about 330° and extending up the valley of the Cumberland River. Minor high angle faults with south-easterly dip have been found in cuttings along the Great Ocean Road, for example at Windy Point.

The arkoses show extensively-developed joints, which are moderately spaced (300 mm to 600 mm), uncemented and generally planar, but some have a slight curvature. They are usually tight, but those that show some evidence of movement are slightly open. Unless significant movement has occurred, the joints generally do not have slickensides. They show a wide variation in smoothness, from quite smooth to moderately

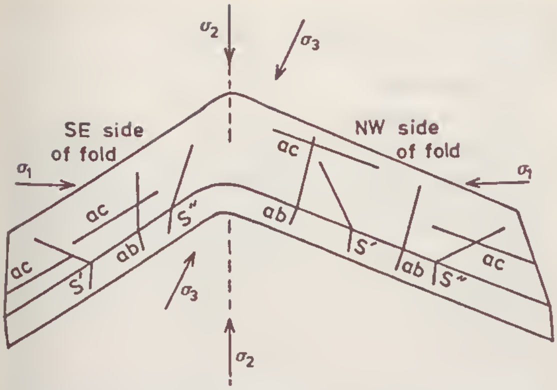

FIG. 4—Block diagram showing relationship of joints and stress directions in the George Anticline; σ_2 approximately vertical, σ_1 and σ_3 almost horizontal.

rough, with the majority smooth. A joint rosette for Windy Point is shown on Fig. 2. These joints are all very close to vertical, the majority of dips being greater than 80°.

A rosette for all joints in the George Anticline is given as Fig. 3. The statistical average of the strike of the fold axis is plotted as B and the nomenclature of the joints is that of Price (1966). The dominant joint direction is similar to Price's S′ shear joint, but the ac tension joint is obscured. Within a fold system, the ac joints normally form a distinct set with symmetrical distribution, whereas the ab joints are generally more dispersed (F. C. Beavis, pers. comm.), and this pattern is observed here. The ac joints are rarely normal to the fold axis (Turner & Weiss 1963) and this is also the case in this area.

Using a method outlined in Phillips (1971) the statistical averages of the two shear joints S′ and S″ were plotted on a stereogram and the σ_1, σ_2 and σ_3 stress directions were obtained. The axis of the intermediate principal stress (σ_2) is shown to be close to vertical, while the minimum principal stress (σ_3) is only 9° from the horizontal (Fig. 4). The stress system outlined above is that under which wrench faulting could be produced.

These results are indirect evidence for the possible existence of a wrench fault at the Cumberland River. The vertical direction of σ_2 would support Hills's (1940) suggestion that the Otways were once covered by Tertiary sediments which have since been largely stripped off as a horizontal σ_2 would be expected when the weight of overburden is small. This contrasts with the idea of Krause (1874), Hall (1909), and Coulson (1938), who pictured the Otway Ranges as an island in the Tertiary seas.

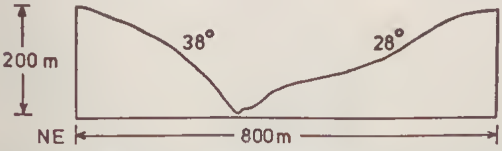

FIG. 5—Idealized valley slope profile in the Windy Point area, looking south-east, with surface slopes in degrees.

GEOMORPHOLOGY

Steep slopes are the most striking feature of the Windy Point area, both along the valleys and the coastline (Pl. 16B). Much of the coastline shows a well-developed shore platform, up to 125 m wide in places, with the slopes above up to 37°.

Three streams, the St. George River, Sheoak Creek, and the Cumberland River, flow into the sea in this area together with numerous small creeks and water courses. Only the St. George River has developed a significant flood plain.

The drainage pattern has two prominent directions. The slope normal to the divide of the updomed Otway Ranges has given a south-east direction of flow, and a direction parallel to the main fold axes (approximately 70°) is clearly shown by the Cumberland and St. George Rivers where massive arkose beds have formed a barrier to river erosion (Fig. 2).

The three rivers all show meandering courses, with cliffed amphitheatres adjacent to the convex sides of meanders. Undercutting associated with the development of meanders caused several ancient landslides adjacent to the St. George and Cumberland Rivers. Rapids are common on all three rivers where interbedded arkose and mudstone alternate rapidly, and gorges and several waterfalls have also developed along the rivers.

SLOPE FORM AND EVOLUTION

Degradation by river erosion is the main factor affecting slope form and evolution, and provides the trigger for mass movement which controls the evolution of the slopes. Slope failures are more common in lightly vegetated or grassed areas. All the valleys tend to show a distinct asymmetry, with the south to south-west facing slopes being approximately 10° steeper than the north to north-east facing slopes. The latter in general have a concavo-convex shape, often with undulations due to landslips on the steeper sections. The south to south-west facing slopes have a convex shape, steepening close to the valley bottom (Fig. 5).

The reason for this distinct asymmetry is not clear as there does not appear to be any difference in structure, or in the depth of weathering. However, the steeper south to south-west facing slopes tend to receive more rainfall from south-westerly storms, and, with increased saturation, they might fail more easily than the north to north-west facing slopes which receive more direct sunlight and hence are drier. On the gentler slopes short, shallow landslips are more common. Throughout the Windy Point area gulleying, tunnelling and slope wash are minor processes compared with landslip activity.

The same type of asymmetry has been studied by one of us (EBJ) in the South Gippsland Hills west of Korumburra where rocks of similar age and structure are found, but with their former dense forest cover largely cleared.

SOILS

The soils developed on the arkose and mudstones of the Otway Ranges are described by Northcote (1962) as hard-setting, loamy soils with mottled yellow clayey subsoils. There is a trend through the profile from a neutral or very slightly alkaline topsoil to a distinctly acid subsoil, with pH = 5. The soil on the arkose is less well developed and not as thick as the soil on the mudstone. In general the soils are clay loams with low to medium plasticity and medium toughness.

QUATERNARY HISTORY

Uplift of the Otway Ranges took place during the Pliocene (Edwards 1962) and has been responsible for the development of the well-dissected topography. The domal uplift of the Otway Ranges was unlikely to have been a continuous event. The presence of hanging valleys (Edwards 1962), cobble beds (Gill 1972) and at the St. George River a high level terrace, all of which are now at an approximate elevation of 7 to 10 m above present sea level, suggest a temporary halt in uplift; however, the hanging valleys and the high level terrace might have resulted from rapid back cutting of the coastal cliffs. These features are considered unlikely to have been produced by a Quaternary higher sea level.

Following the final uplift in the Quaternary active downcutting of the rivers has continued. Evidence of minor fluctuations in sea level generally would not be preserved in this area due to the active downcutting of the streams and the retreat of the coastline by erosion. River terraces at approximately 1·5 m above present sea level are developed near the mouths of the three main rivers, and a 3 m terrace has also formed at the Cumberland River mouth. These terraces can be compared with the mid-Holocene maximum sea level of 2 m to 3 m suggested by Gill (1961) and Jenkin (1968).

SLOPE STABILITY

The early Cretaceous arkose and mudstone rocks in the vicinity of the Great Ocean Road near Lorne are well known for their slope instability, both in relation to recent road construction and to the mountainous Otway Ranges coastline which has been eroding during the Quaternary. Five slope failures have occurred in the area studied but only the one at Windy Point has achieved any notoriety. Along most of the south-east side of the Otway Ranges the bedding dips seaward, the arkose is well jointed, and comparatively thin clay strata are present; as a result the ocean-facing slopes are in a metastable state, and disturbance of their toe regions can be a trigger for failure.

THE WINDY POINT LANDSLIDE

Windy Point is 3·2 km south of Lorne, on the Great Ocean Road (Fig. 1 and 2) and was the location of a large rock slide from 1968 until late 1971, when the slide was stabilized by cable anchoring. Windy Point is a minor headland of massive, strongly-jointed Early Cretaceous arkose, with minor thin mudstone beds which have largely decomposed to a silty clay (Pl. 16A). Two near-vertical prominent joint sets at roughly 90° to each other are present, but statistically

FIG. 6—Equal area projection of planar discontinuities (bedding and jointing) at Windy Point. 102 points.

there is a large range in individual values. The bedding strikes at 74° east from true north and dips at 27° south-east. An equal area projection of planar discontinuities for Windy Point shows the statistical dominance of the bedding (Fig. 6).

Windy Point is the site of an older rock slide, and removal of a small quantity of rock from its toe during road widening in late 1968 was enough to upset the delicate balance and initiate movement. Average movements of up to 2 cm per day, which greatly increased following rain, were observed high up on the slope. The opening of fissures Y-Y′ and Z-Z′ along the joints (Fig. 7 and Pl. 16A) was observed during late 1968 and 1969, with substantial movements during October 1970, when the direction of movement changed from down dip (164°) to more directly towards the road (120°), indicating an advanced state of failure. The fissures were then up to 20 m in depth, and approximately 200,000 tons of rock were moving down dip (Williams & Muir 1972).

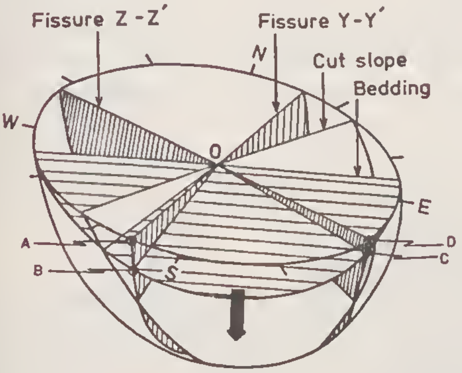

Fig. 7—Spatial diagram for Windy Point (method after John 1968). Note that the cut slope has removed support from the block bounded by A, B, C, D and O which may now slide along the bedding plane in the direction of the arrow (see also Pl. 16A).

After considering the possibility of relocating the Ocean Road, or causing the slide to fail rapidly by blasting or irrigating, it was decided that the only practicable solution was to stabilize the slide with cable-anchors. Thirteen drainage holes up to 53 m long, and inclined at 5° to 25°, were also drilled into the slope. Forty-five tensioned cable-anchors from 18 m to 43 m long provided a total anchor force of 7,740 tons and a factor of safety of 1·07. The anchors were distributed about the lower part of the slide to provide support for the entire rock mass. The shear strength of the slip plane was assumed to be frictional and since the failure conditions had just been reached it was also assumed that the angle of friction between the stable and sliding rock was equal to the dip of the slip plane, that is 27°.

Causes of Failure

The factors which contributed to the unstable situation are summarized by Williams and Muir (1972) as 'the steep natural slope which rises to a height of 330 m; the seaward (southerly) dip of about 27°; the presence of at least two thin (12 cm and 40 cm) beds of silty clay which partly underlie the massive beds of jointed sandstone and which intersect the lower part of the slope near road level. Other major factors include the two prominent and persistent sets of subvertical joints, the numerous minor joints at various angles; the numerous surface fissures and craters which resulted from earlier movements'.

The two main joints are the S′ shear joint and the ab joint which are found over the whole area (Fig. 3). As most of the rain water was reaching the silty clay horizons via the joints and fissures, it is quite possible that a considerable hydrostatic head was built up. Although most of the rock involved in movement is fresh, the mechanism of breakdown of the arkose influences the type of movements, with the feldspars remaining quite fresh while the cement breaks down. The weathered arkose is very friable, and upon failure the weathered rock would tend to crumble and topple, rather than failing by flow as might be expected if the feldspars produced illitic clay. The presence of coal seams, and of the swelling clay mineral chlorite (shown by X.R.D.), should also aid the breakdown, and the minor interbeds of clay would probably show a reduction in cohesion with time. Following heavy rains, water presumably percolates along fractures, and accumulates on top of the clay. Although the permeability of the clay zone would be low, it would soon absorb water until the clay zone would no longer exhibit resistance to shear. The interbedded clays at Windy Point may also have become thixotropic. On the other hand, the weathered arkose in the vicinity of the joints, being granular and having a much smaller pore space, would dilate as it became water saturated (Kerr & Drew 1965). This would provide a greatly increased load on the much weakened clay zone and the arkose would start to slide on the clay.

Another possible factor in the stability of the slopes in the Otway Ranges is the presence of high salt levels. Analysis of water samples from Sheoak Creek gave the following results: Calcium, 4 ppm; Magnesium, 3 ppm; Sodium, 19 ppm; Sulphate, 6 ppm; Chloride, 76 ppm.

Analyses from other parts of the Otway Ranges give similar results. The high content of Na^+ and Cl^- ions suggests that during storms salt spray is carried inland. The high NaCl in the rivers represents the removal of largely surface salt by normal erosion.

The soil profile in the area is distinctly acid, and persistent acid leaching depletes metal cations such as sodium and calcium (Prior & Ho 1972). The presence of NaCl would have two effects on the illitic and kaolinitic clay. NaCl is a strong electrolyte and by the law of mass action would replace exchange ions already present on the clay and cause them to flocculate, thus tending to stabilize any uniform slope. However, with a slope consisting of a well jointed arkose overlying clay, the salt could be leached down fissures into the clay horizon and by mass action effects would replace the exchangeable ions (largely H^+ and K^+), and possibly cause a contraction in effective clay volume since the replacing ion has a smaller hydrated ionic radius (R. J. McLaughlin, pers. comm.). This contraction could remove support from the overlying arkose and if it were already in a delicate state of stability it might fail. The latter situation would exist in most of the Otway Ranges, but the former situation exists on the slope at Eastern View to be described later.

Shallow slides in the Windy Point area appear to be the result of shrinking and cracking of the surface clay horizons during dry periods, and then during heavy rainfall water percolates through the cracks leading to quick swelling and weakening of the fractured soil mantle. The average soil from the area studied has a liquid limit of 48, a plastic limit of 13 and a plasticity index of 35. The relatively high liquid limit and plasticity index is a reflection of the high illite and chlorite content.

Slope Stability Map

Methods of prevention of slope failures should be applied to the most unstable slopes in an area. In an attempt to assess the relative stability of slopes in the area studied, a 'Slope Stability' map has been devised (Fig. 2). 'Slope Category' maps are of limited value as they depict only one of the factors influencing slope failures. Other representations of the stability of an area (e.g. Erskine 1973) depict only what has already occurred, and do not allow any prediction of future movement.

The method used in preparing the slope stability map was to look at the main factors influencing slope failures and then assess their relative importance in a simple quantitative way. Appendix I shows the criteria and method used in the construction of the map. Any slope stability map will unfortunately be subjective. The use of whole numbers is an attempt to remove at least part of the subjectivity, while still remaining relatively simple.

The value of the map is that anyone not familiar with the area can see at a glance which areas are the most unstable and hence require preventive action. For example, the section of the Great Ocean Road at The Spit which has been rated critically unstable on Fig. 2 is shown in Pl. 16B. If inadequate criteria are used or an area is poorly assessed some unstable areas may of course remain undetected.

The criteria used for the Windy Point area should be applicable to most of the Otway Ranges where similar geological and geomorphic conditions exist. Different criteria would be needed for other areas.

Summary

Natural slope failures and failures due to road construction occur in the Windy Point area. The Early Cretaceous arkose and mudstone is strongly jointed, with steep slopes, and weathers along bedding and joint planes leading to crumbling, toppling and rock sliding. Stabilization of slopes may be expensive as at Windy Point where $A200,000 has been spent. Preparation of a slope stability map can help in delineating areas of possible failure.

EASTERN VIEW

At Eastern View, 110 km south-west of Melbourne (Fig. 1) a slope shows a number of mass movement features which are not present at the forested Windy Point area. The slope was cleared near the end of the last century, and numerous failures have taken place, both on the main north-east-facing slope which has a stream below, and on the steep slope facing the ocean and the Great Ocean Road.

Geological Setting

The Early Cretaceous mudstone and arkose underlying the slopes has been completely weathered to a silty clay for a depth of 3 to 4 m. Slope failures are generally quite shallow and take place in the weathered mantle above the rock. Landslip activity is the main process of erosion acting on the slopes, but gullying and piping as well as some flows are active on the lower part of the north-east-facing slope.

Landslips Present

Most slope failures at Eastern View are shallow compound rotational slides, with a D/L ratio ranging from 1/60 to 1/30 (D = depth to failure surface from original surface, L = length; Crozier 1973). Nevertheless, most failures have an element of flow.

There is a high correlation between slope angle and slide concentration. Failures are most common on slopes greater than 16°, which appears to be the critical angle of slope failure. The morphology of the slides indicates rotation, and a major rotational slide has occurred on a slightly steeper part of the north-east-facing slope (Pl. 17A). The lower part of the slope first failed in 1913, the removal of support for material higher up the slope giving a non-equilibrium situation. As each successive slide worked its way up the slope further removal of support took place, and the slide reached nearly to the top of the slope in 1952. Since then reslipping of the earlier slides has occurred, with the prominent slide shown in Pl. 17A taking place in 1971. Altogether five cycles of movement can be determined.

The ocean-facing slope has a multiplicity of flows and rotational slides. Road construction at the foot of the slope is clearly a major contributing factor, but most of the slides took place one night in 1952 when 230 mm of rain fell. On slopes greater than 20°, which are often up to 30°, a regular succession of terracettes is developed. Terracettes tend to be on the edges of previously slipped areas where the unweathered rock is relatively close to the surface, and have a stabilizing influence, preventing larger rotational slides occurring.

SUMMARY

Shallow compound rotational slides and flows at Eastern View are due to steepening of slopes by streams, the ocean and road construction. Clearing of the land and grazing by cattle have also favoured landslips, and movement has often been triggered by rainfall.

PARWAN VALLEY AND WERRIBEE VALE AREA

The Parwan Valley and Werribee Vale area is near Bacchus Marsh, which is approximately 50 km west-north-west of Melbourne (Fig. 1). It represents two of the worst sites of mass movement and other types of erosion to be found in Victoria. Particularly in the Parwan Valley gully erosion, piping and sheet erosion are the main

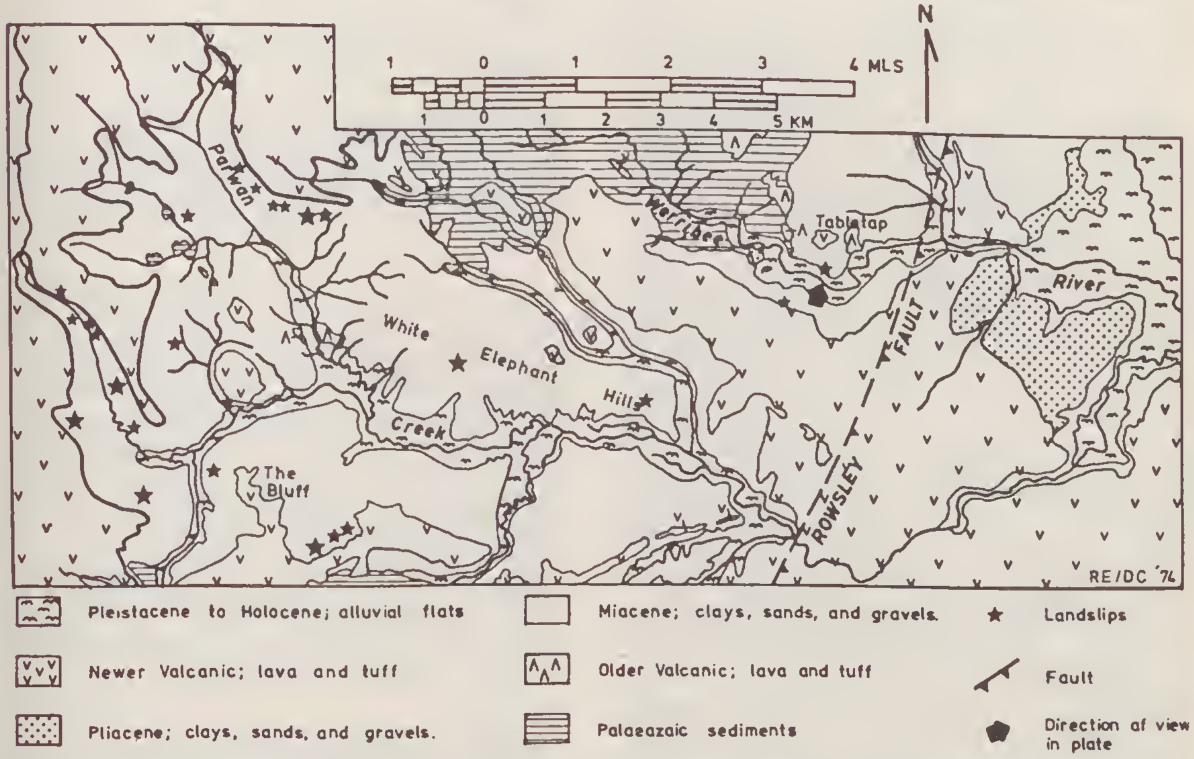

FIG. 8—Geological map of the Parwan Valley and Werribee Vale area (after Forbes 1948) showing landslips in Miocene sediments mapped from air photos and field reconnaissance (see also Pl. 17B).

processes of degradation but landslips of various ages are common also.

GEOLOGICAL SETTING

Unconsolidated Miocene sediments underlie a relatively thin cover of Newer Volcanic basaltic lava flows (Fig. 8). These horizontally-bedded fluviatile Tertiary sediments vary greatly in composition and include incoherent boulder deposits, sands and clays, ferruginous sandstones and mudstones, and almost pure limonite. The sediments are very poorly cemented and their resistance to erosion is weak. The overlying basalt forms a protective cap but the easy erodibility of the sediments leads to undercutting of the basalt capping.

Movement along the Rowsley Fault scarp in the late Pliocene and Pleistocene has elevated the headwaters of the streams to the west by up to 170 m (Forbes 1948), and deep valleys have been cut by the Parwan and Yaloak Creeks, and the Werribee River (Fig. 8).

LANDSLIPS PRESENT

Landslips are playing an important part in the enlargement of the Parwan Valley and their influence is seen in the steep, broken, white-streaked, and unstable slopes along the valley wall. Landslips are particularly abundant along the steeper cliff sections below the basalt flows. Forbes (1948) believes that the residual ridges and hills occurring within the valley (some of them capped with basalt which is at a lower level than that of the surrounding plain) probably represent landslipping on a grand scale. Rotational sliding around basalt residuals is common.

The main soil type in the Parwan Valley is a sandy clay loam with a columnar and blocky structure which permits the entry of water and thus facilitates erosion. X-ray diffraction shows that besides quartz and feldspar, there is much kaolin and some illite present. The predominance of kaolin is shown in the low liquid limit of 36, a plastic limit of 20 and thus a plasticity index of 16. These results agree with the observations that slipping (usually consistent with a higher liquid limit) is subordinate to gully erosion and piping. A viscosity test performed on the Miocene clay showed that it is fairly thixotropic, and once the heavily saturated mass has started to move there is little resistance to retard its motion, and so flows as distinct from slides are predominant.

Most slips in the Parwan Valley are shallow, elongate earth and mud flows with an average D/L ratio of 1/40. They are generally not very recent and have a characteristic rapidly-undulating surface expression with an indistinct head scarp and toe.

A very deep rotational slide is present on the flanks of Table Top in the Werribee Vale area (Pl. 17B and Fig. 9). The slide has a D/L ratio of 1/11 and is in Miocene sands and gravels with a lateritized 'ironstone' capping. In part the slide is due to the presence of an old concrete-lined irrigation channel constructed on the slope in the early part of the century. Approximately 100 m of the channel were carried away in the slide (Harding 1952). The main trigger was exceptionally heavy rain that fell during 1952. Several cycles of sliding are evident although the whole slide would have occurred quite rapidly. The steep scarp is now being heavily eroded by piping. Just to the west of this slide is a large amphitheatre-shaped region caused by several old deep-seated rotational slides which have produced a characteristic 'bumpy' area.

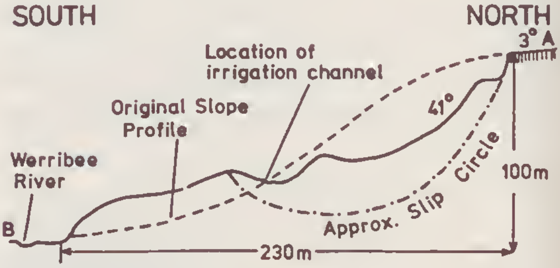

FIG. 9—Sketch cross-section of rotational landslide near Table Top, Werribee Vale, surveyed by pacing and Abney level (see Fig. 8 for location). Vertical shading indicates lateritized surface of Miocene sediments; surface slopes in degrees. For A-B see Pl. 17B.

More landslips occur in the upper part of the Parwan Valley than in the part closer to the Rowsley Fault (see Fig. 8). This appears to be related to the grain size of the sediments. Clay and silt-sized sediments occur to the east closer to the Rowsley Fault, and these erode mainly by sheet wash. In contrast, clay and sand-sized sediments in the upper part of the valley fail largely by flowing, as water can enter the sediments more easily and saturate them.

The burrowing work of rabbits, overgrazing and the removal of trees and much natural vegetation are significant factors causing slipping, gullying, piping and sheet erosion.

SUMMARY

Shallow earth and mud flows often up to 300 m long are common on slopes greater than 25° in the Parwan Valley, and several deep rotational

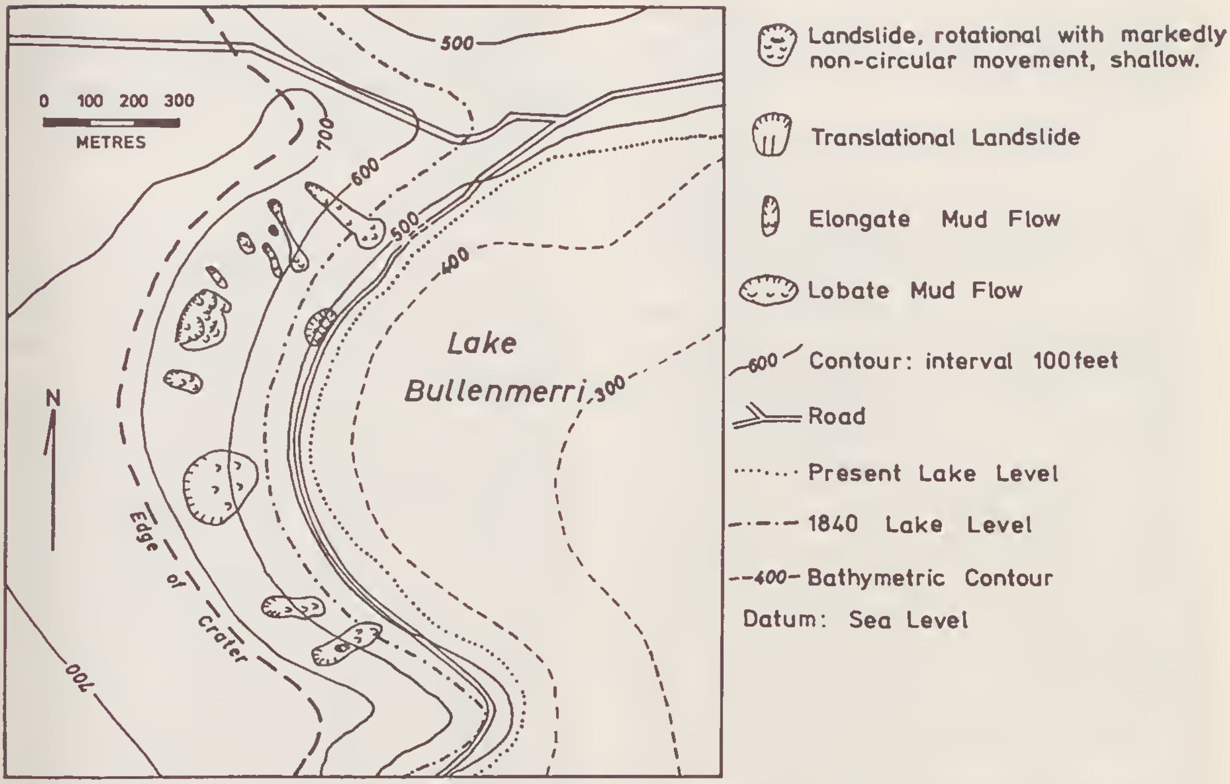

FIG. 10—North-west corner of Lake Bullenmerri crater showing location of landslips in September 1973 based on field reconnaissance. Base map, contours and lake levels after Currey 1970).

slides are also found in the area. The clay-rich poorly-cemented Tertiary sediments also erode readily by gullying, piping, and in some areas sheet erosion, and the effect of European settlement has been to increase the rate of erosion.

LAKE BULLENMERRI

Lake Bullenmerri is a lake in a volcanic crater near Camperdown, nearly 200 km west-south-west of Melbourne (Fig. 1). The crater was formed by a late Quaternary eruption of maar type, and is part of the Newer Volcanic province of south-eastern Australia (Ollier & Joyce 1973). Since the slopes were cleared of vegetation around the turn of the century (E. D. Gill, pers. comm.) the upper part of the north-west crater wall has been degrading by land slipping. A complete spectrum of different types of shallow landslip is present (Fig. 10).

GEOLOGICAL SETTING

The walls of the volcanic crater above Lake Bullenmerri consist of horizontal marine Oligocene siltstone and sandstone capped by approximately 20 m of Newer Volcanic lavas and tuffs. The slope developed on the sediments is predominantly concavo-convex with a relatively sharp break of slope at the base of the Newer Volcanic capping. The soil on the sediments is a silty clay loam with a depth of 1·5 m. Fragments of sedimentary and volcanic rock are common. Sliding is largely confined to slopes steeper than 20° on Tertiary sediments. A series of terraces indicate former water levels, with one prominent terrace about 15 m above present lake level.

LANDSLIPS PRESENT

Bullenmerri is a good example of what at first glance appears to be a few landslips, and a chaotic spread of slipped material, which, with more detailed examination, reveals an interconnected complex of numerous slides and flows. A number of different types of slips are present, the distinction being the D/L ratio. Shallow slips from 0·5 m to 1 m deep are either lobate or elongate mud flows, with flow occurring in the heavily oversaturated A and B soil horizons. One elongate mud flow is approximately 125 m in length but only 8 m wide, with a depth of 0·5 m. It has a D/L ratio of 1/250. These elongate mud flows occur on the relatively steep slopes of 24°, while the lobate mud flows are found on gentle slopes of less than 10°. Shallow non-circular rotational slides occurring on the steep slopes have a D/L ratio of 1/15.

In 1840 the lake level was 554 feet (Fig. 10), and in 1918 513 feet (Currey 1970). Three slides are below the 1840 lake level and field observations indicate that two of these slides are older than slides higher on the slope. Thus 1840 is a maximum limit to the age of sliding and most slides are likely to be much younger.

Three broad periods of landslip activity can be distinguished. An older cycle of large, deep, rotational slides has a present surface expression of broad, heavily-grassed amphitheatres and extensive, ill-defined toe mounds. This first cycle could possibly be related to exceptionally heavy rainfall recorded in 1911, 1916 and 1924. (See Evans & Joyce 1974). An intermediate age of slipping, possibly in 1952, is expressed as closely-spaced, sharp undulations of the ground surface with distinct boundaries at the toe and flanks. Most slips shown in Fig. 10 are of this age. Finally, resliding of the lower parts of the intermediate-age slips is evident in some elongate mud flows, and a shallow rotational slide took place in early September of 1973 following heavy rain. No apparent relationship exists between the falling of the lake level and the location of landslips on the slope.

The abundance of failures on the north-west slope can be related to the micro-climate. This south-east facing slope receives less sunlight and is thus more water-logged than the adjacent non-slipping slopes.

The inorganic clay of high plasticity present in the B horizon has a liquid limit of 77, a plastic limit of 29, and thus a plasticity index of 48. Clay mineral analysis shows the presence of montmorillonite (due to weathering of the volcanics), chlorite and kaolinite. Montmorillonite is well known for its role in facilitating failure. The high liquid limit shows the strong tendency to flow and is largely a reflection of the montmorillonite content. The nature of the clay minerals and the field observations indicate that when saturated the clays are very thixotropic.

Summary

The central slopes of Bullenmerri reveal a complex pattern of old and young slips with mud flow being the principal degradation process. Water seeping below the Newer Volcanic capping produces an extreme degree of water saturation in the Oligocene silts and clays and this, combined with the presence of montmorillonite and swelling chlorite in the soil, produces unstable slopes. On the steeper slopes, slope evolution proceeds by rotational slides and flows with undercutting and collapse of the Newer Volcanic capping. Major lake level changes have produced minor terraces, with some mud flows developing at the heads of the benches.

CONCLUSION

This study of four areas of landslide activity in Victoria has shown that the Early Cretaceous arkose and mudstones and the Tertiary sandstones and mudstones are the main rock types which have a high susceptibility to failure.

The noted instability of the Early Cretaceous arkose and mudstones of the Otway Ranges is due to the strong jointing, youthful topography, active undercutting by the ocean and rivers, and most significantly, weathering along the planar discontinuities of bedding and joints. The presence of relatively fresh feldspar in the weathered arkose leads to crumbling, toppling and rock sliding rather than flow. The abundance of chlorite and a reduction in cohesion of the interbedded mudstones with time also aids failure. Salt spray may have a stabilizing influence on slopes of uniform composition, but in other cases may lead to slope failure. A slope stability map devised for the Windy Point area, south of Lorne, has been used to assess the slope stability so that dangerously unstable areas can be delineated.

The slope at Eastern View shows predominantly rotational slides in the weathered silty clay soil. These slope failures are closely related to river, ocean and road undercutting.

Slope failures in the Parwan Valley and Werribee Vale area are due primarily to the high clay content of the poorly cemented Tertiary sediments. Flow failures in the soil developed on Tertiary sediments on the north-west edge of Lake Bullenmerri appear to be aided by the presence of montmorillonite from decomposition of the overlying volcanics. The soils are also prone to saturation from water seeping below the volcanic capping.

ACKNOWLEDGMENTS

The authors wish to thank Mr. Allan Muir of the Country Roads Board, Victoria, for his help in obtaining photographs and other information for the Windy Point area, and Mr. Don Campbell for redraughting the figures.

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Appendix 1

CRITERIA FOR CONSTRUCTION OF A SLOPE STABILITY MAP FOR THE WINDY POINT AREA.

The stability of any locality is assessed using the criteria listed below and a corresponding numerical value assigned. The locality is then rated in one of five categories, ranging from Stable to Critically Unstable, according to the total numerical value.

1. Angle of Slope:	
(a) 0– 5	0
(b) 6–15	1
(c) 16–26	2
(d) 27–42	3
(e) Over 42	4
2. Vegetation:	
(a) Heavy Vegetation	0
(b) Light Vegetation	1
(c) Grass	2
(d) No Vegetation	3
3. Road Cutting	4
4. Cattle Grazing	1 or 2
5. Proximity to Water Table or Springs	0, 1, 2 or 3
6. River Erosion	1
7. Jointing	1
8. Bedding Dips in Direction of Potential Failure	1 or 2
9. Previous Landslide Activity	2

Stability Ratings:

1. Stable	$\leqslant 5$
2. Potentially Unstable	6–9
3. Unstable	10–13
4. Very Unstable	14–15
5. Critically Unstable	$\geqslant 16$

The maximum possible value is 20 with a common Ocean Road cutting having a value of 15 and a common hill slope, 9.

Discussion

The subdivision of the slope angles is largely arbitrary. It is assumed that the steeper the slope, the greater the likelihood of failure. The 27°-42° grouping represents the range of the angle of friction values for different types of failure planes observed in the Otway Ranges. It is also assumed that the frequency of shallow mass movements under undisturbed forest is lower than that under scrub or pasture (Campbell 1945). Road cuttings have been given a very high priority (4) as the method of construction, largely blasting, and the vibrations of traffic are believed to affect significantly the stability of the slopes in the immediate vicinity. The proximity to the water table and thus the degree of saturation is a significant but highly variable factor. The rock type is presumed to be homogeneous over the area studied but its structure (largely jointing or bedding plane orientation) may be important. Evidence of previous landslide activity is considered significant as further movements can occur more easily if part of a slope has previously failed. The influence of undercutting by the ocean is not considered in this area as the Ocean Road runs along the length of the coastline.

DESCRIPTION OF PLATES 16 AND 17

Plate 16

A.—Oblique aerial photograph of Windy Point, near Lorne (see Fig. 2). Note vehicles on road for scale. Fissures Y-Y^1 and Z-Z^1 are also shown in Fig. 7 (Country Roads Board, Victoria, 70-5888, 22 March 1971).

B.—Great Ocean Road at The Spit, approximately 1·5 km south-west of Windy Point (see Fig. 2). Arrows indicate the old escarpment at top right indicating earlier movement, and the tension cracks developed above the road cutting in the centre (Country Roads Board, Victoria, 70-5883, 15 January 1971).

Plate 17

A.—Rotational landside at Eastern View, looking south-west (R. S. Evans, 15 July 1973).

B.—Rotational landslide in Miocene sediments near Table Top, Werribee Vale (for A and B see Fig. 9) (A. A. Baker 1956).